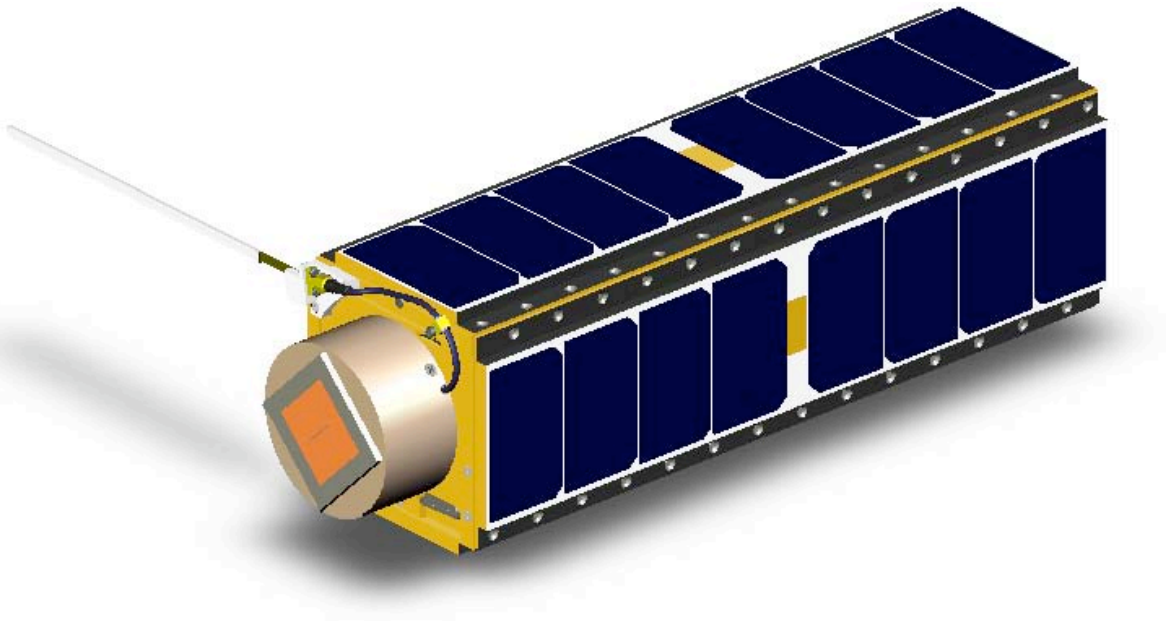
GENESAT-1

Space Technology Demonstration



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1.0 Spacecraft Overview

The GeneSat-1 spacecraft and launch support systems are based on the University CubeSat standard. The standard consists of an approximately 4" x 4" cube configuration. Three of these cubes can be placed inside a Poly Picosat Orbital Deployer (PPOD), which was developed by Cal Poly San Luis Obispo to contain and then deploy the cubesats once on orbit. The GeneSat-1 configuration is actually a single "triple cube".

1.1 Satellite

The GeneSat satellite (Figures 1.1-1 and 1-1.2) is the integrated system comprised of the satellite bus and the payload. The bus provides power all power, uplink/downlink communications, and attitude determination. The bus also manages remediation of single event effects. The payload provides accommodation for the biological experiment, associated support hardware, fluidics, electro-optics, electronics, and sensor systems.

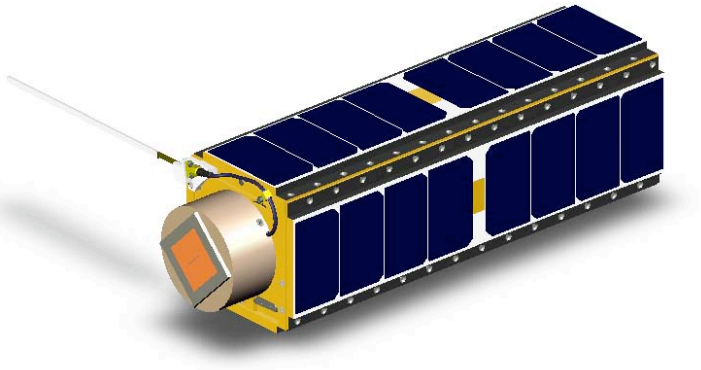

Figure 1.1-1, GeneSat Satellite

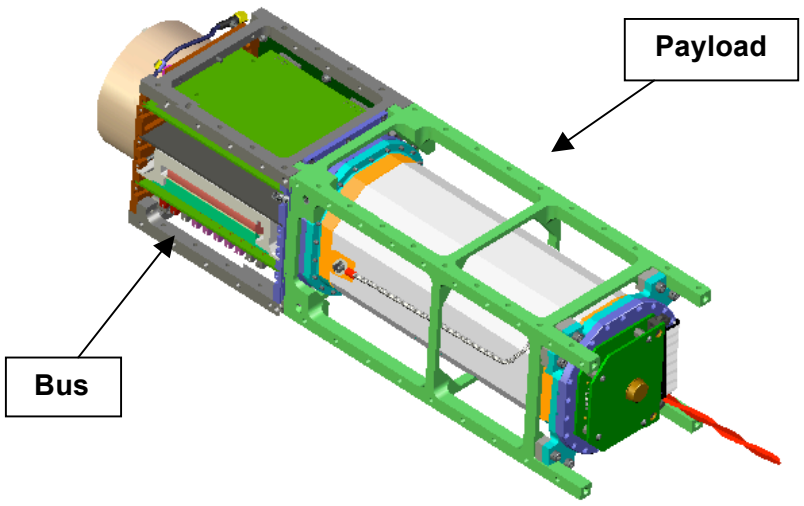

Figure 1.1-2, GeneSat with the Solar Arrays Removed for Visibility

Figures 1.1-3 and 1.1-4 shows the GeneSat payload engineering development unit. The payload system is the primary science payload and all of its integrated subsystems. This system is integrated into the Spacecraft, which is subsequently integrated into the Spacecraft Deployment System (on-orbit deployer) and then the Launch Vehicle.

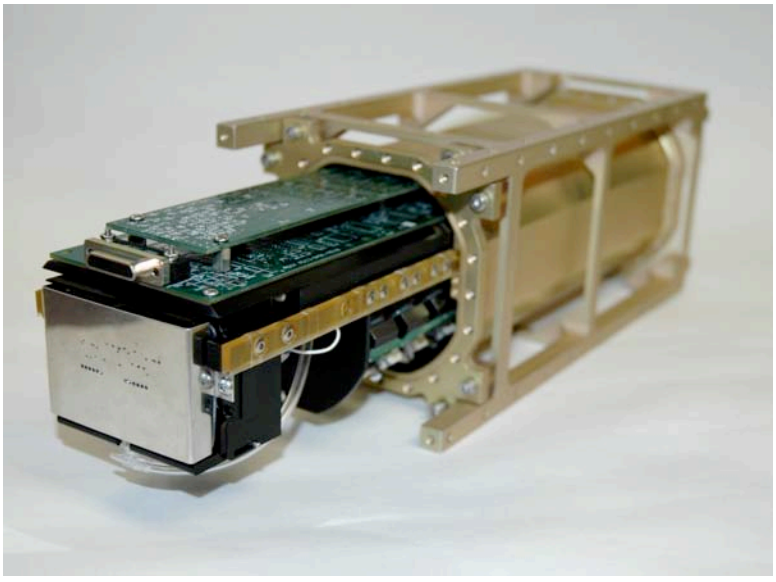

Figure 1.1-3, Payload Assembly Partially in Pressure Vessel

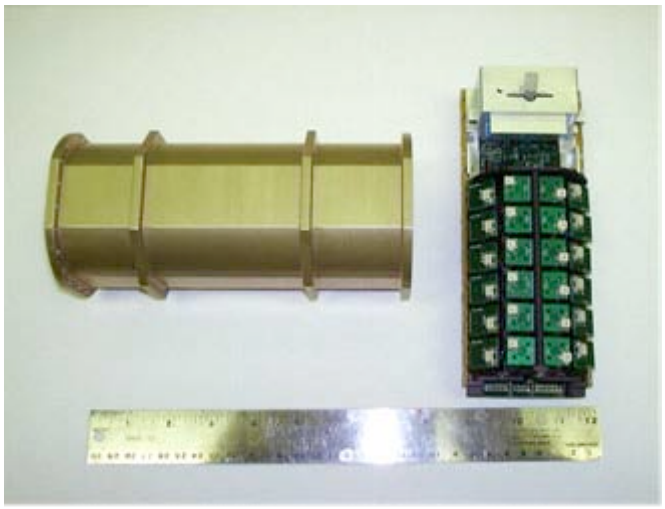

Figure 1.1-4, GeneSat EDU Payload

1.1.1 Fluidics Wellplate Card

The primary function of the Fluidic Subsystem is to contain biological samples in an array of twelve assay wells and allow fluid delivery to the assay wells through micro-fluidic channels. Ten wells contain biological samples and two wells contain optical calibration material. The fluidic system is illustrated in Figure 1.1.1-1.

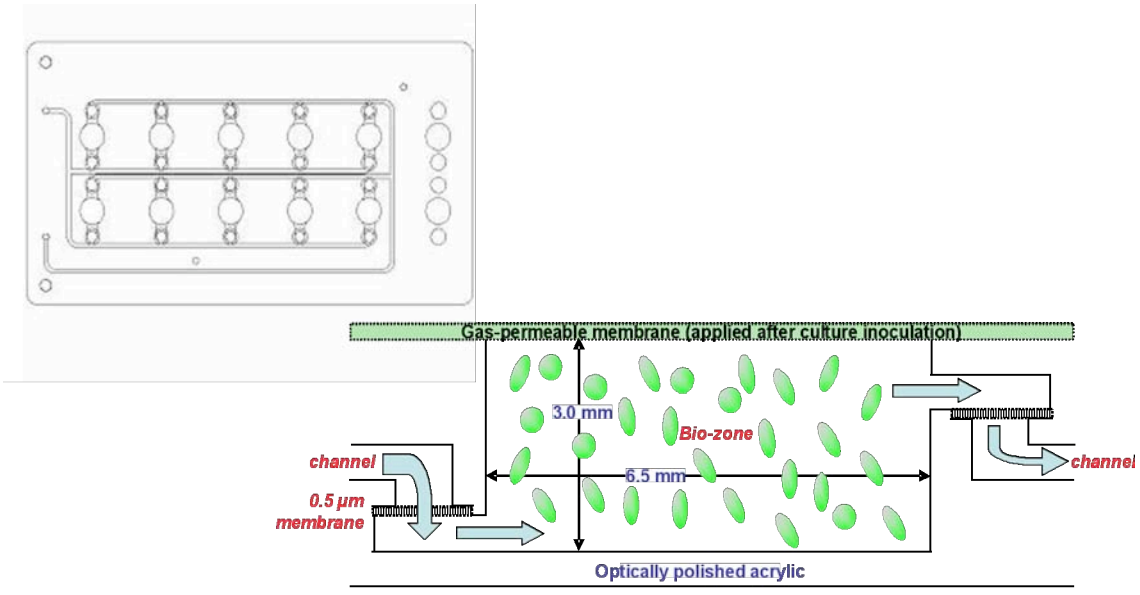

Figure 1.1.1-1 Fluidics Schematic

Samples of *E. coli* are dispensed into an assay well with a 6.5 mm diameter and 3.0 mm depth. The assay wells are spaced on an 18 mm grid to facilitate ground-based studies using laboratory equipment that can read SBS standard microtiter plates. After *E. coli* introduction, the assay well is sealed with a membrane using a pressure-sensitive adhesive, and the assay wells are filled with stasis media via the micro-fluidic channels. The fluidic card features one inlet micro-fluidic channel and one outlet micro-fluidic channel per assay well. Membranes across the micro-fluidic channels on either side of the assay well allow fluid flow but prevent *E. coli* from escaping through the micro-fluidic channels.

During experiment initiation, nutrient media required for *E. coli* growth is delivered to each well through the micro-fluidic channels using a pump and valve system which drives fluid from a media bag to the card via tubing and fluidic connectors (the pump system is part of the mechanical subsystem). The stasis media is displaced by the nutrient media and exits the assay well.

1.1.2 Optics Module

The GeneSat experimental payload was designed to perform both fluorescence and optical density assays of biological specimens in an automated fashion. Please refer to Figure1.1.2-1.

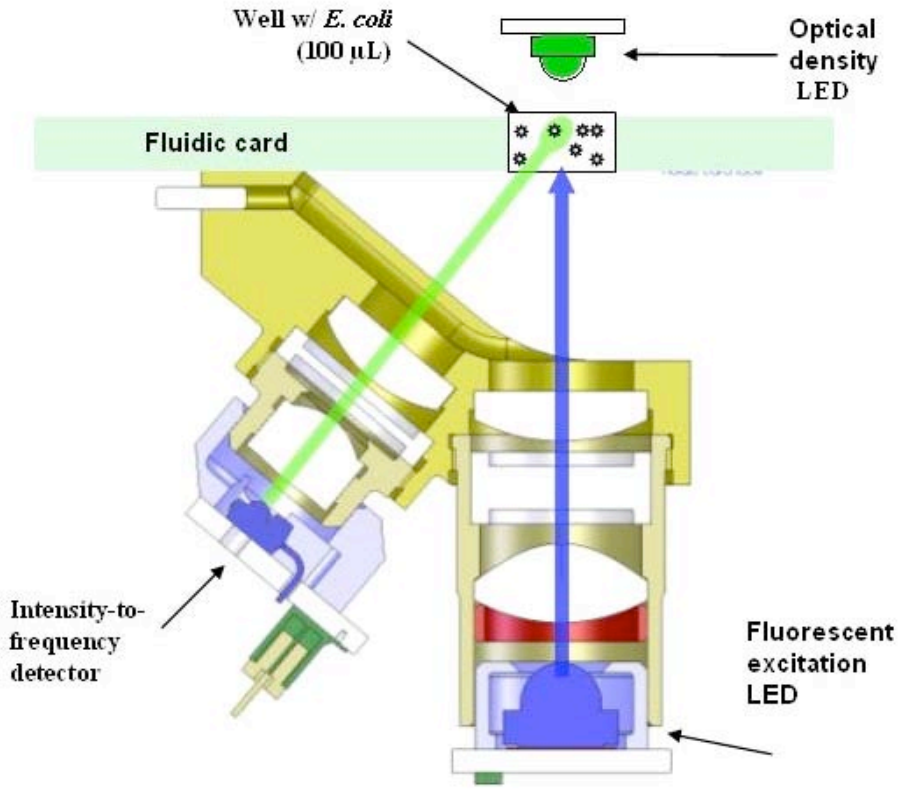

Figure 1.1.2-1 Optics Subsystem Schematic

The biological sample of interest, in this case *E. coli*, is placed inside the fluidic card wells. A complete optics unit sits below each well for a fully redundant assay system. The sample is excited with blue light (wavelengths of approximately 460 - 490 nm). The tagged fluorescent proteins of the sample respond by emitting green light (wavelengths of approx. 505 - 530 nm) which is detected by a photodiode. A set of off-the-shelf lenses and color filters ensure that only blue light of the desired wavelengths reaches the sample and only green light of the desired wavelengths reaches the detector.

An optical density (light scattering) measurement is taken using a green LED that emits in the same wavelength range as the fluorescence from GFP. The LED is mounted in a PC board above the fluidic card well and uses the same collection optics as for fluorescence to measure light scattered by the sample. The amount of scattered light was shown in the laboratory to be directly proportional to the organism population of the fluidic well.

1.2 Spacecraft Bus

The Spacecraft bus system carries the GeneSat payload throughout the mission. The bus provides all power and uplink/downlink communications. The bus also manages remediation of Single Event Effects not corrected by the payload. Figure 1.2-1 shows the bus with electronics in place (payload frame extension areas, the locator beacon, antennas, and solar arrays are not shown).

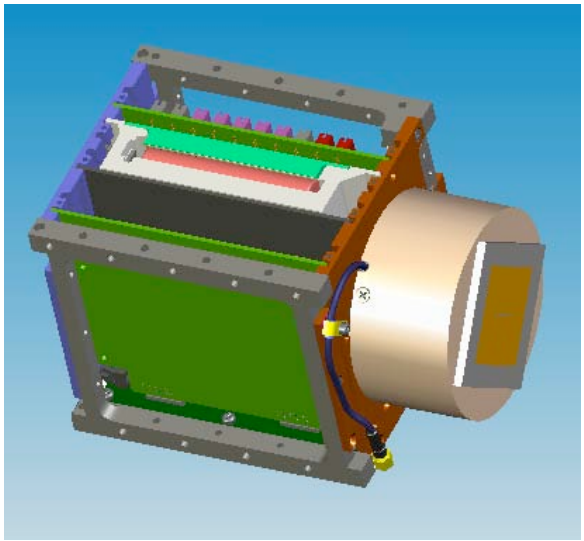

Figure 1.2-1, Satellite Bus / Beacon Assy

2.0 Demonstration Overview

With the high cost, long wait times and overall inaccessibility of the space shuttle and ISS for the use of life sciences experiments there is a need for a more accessible and lower cost alternative. The aim of the GeneSat mission was to validate the use of low cost cubesat satellites as a novel platform for space life sciences research. The GeneSat satellite was capable of autonomously performing a series of steps that would allow for the execution of gene expression studies using microorganisms.

The GeneSat mission demonstrated that microorganisms that can survive the rigors of transport, pre-launch, and launch, can be used in future experiments. Researchers with GFP promoter reporters for their genes of interest can readily use the GeneSat platform to test the effects of the space environment on the expression of these genes. Furthermore, the hardware used in GeneSat has been validated and can now be used as a basis from which to add features and elements of interest to research scientists.

3.0 Test Design

The GeneSat was a technology demonstration of the hardware and the biology used was chosen for it's ability to aid in the hardware validation. Two E. coli strains harboring GFP containing plasmids under the control of two different constitutive promoters were chosen. These strains were chosen based on their performance in a number of different tests including: long term survival in stasis, biocompatibility with hardware materials, and reproducibility of GFP expression. Furthermore, two strains were chosen as an added measure of security should some unforeseen event affect one of the strains.

The fluidics cards for both Flight Units were loaded with the two strains and also included one well loaded with no cells that would serve as an internal control for sterility and other fluidics problems. Fluidics cards were both loaded from the same batch of cells, prepared on 11-1-2006, and actual load dates differed by only one day: load 1 on 11-3-06, load 2 on 11-4-06. Once both GeneSat Flight Units had been loaded, they were kept in the same place and treated the same from this point on including transport to Wallops for integration. Only after one of the two units was chosen for integration into the rocket were the two units separated. The unit not integrated was hand carried back to Ames and used as the ground control for the GeneSat experiment.

4.0 Mission Team (MT)

The Mission Team for GeneSat-1 is:

Mission Manager	B. Yost
Flight Segment Lead	C. Friedericks
Ground Segment Lead	C. Kitts
Lead Technologist	A. Ricco
Lead Biologist	M. Parra

The MT was augmented by systems leads, as required during the various phases of the mission. Specifically, CalPoly SLO supported hardware integration activities, and other ARC personnel assisted with logistics and transportation to/from the launch site. C&DH personnel were also heavily involved with critical mission decisions.

The MT met daily at 9:00 AM PST and reported directly to the Project Manager. A mission operations log was established and maintained by the Operations Team (Santa Clara University), which also included a dashboard function that illustrated the status and current condition of the spacecraft and mission, and also summarized experimental and engineering data. (See http://genesat1.engr.scu.edu/dashboard/index.htm)

5.0 Pre-Mission Operations Summary

Biological specimens were loaded into the GeneSat-1 spacecraft at ARC prior to transportation to Wallops Flight Facility (WFF). Following the loading procedure, functional tests were performed to verify the GeneSat-1 spacecraft is in flight readiness condition.

Following loading, all GeneSat-1 flight systems, GSE, and support hardware were hand carried on commercial airlines to WFF from San Jose. Special provisions (used on other flight campaigns) were made to allow the flight hardware systems to pass through security with a minimum of handling and inspection.

Upon arrival at WFF, the ground processing team performed a limited set of functional procedure to ensure that the flight systems were not damaged during transport. This included a brief activation of the beacon and data communication systems.

Following successful completion of the functional tests, the GeneSat-1 spacecraft was configured to the “Arm Experiment” state, which enabled the onboard time-out clock, and placed the spacecraft in flight configuration. GeneSat-1 was then loaded into the P-POD, and the power inhibit switch (“foot switch’) was set. The P-POD door release mechanism was secured and the entire PPOD/GeneSat-1 package attached to the P-POD adapter plate.

The flight package was then mounted to the Minotaur 1 LV by the resident Orbital Sciences engineers, and the electrical connection for the door release signal was also mated.

6.0 In-flight Mission Operations

The original launch was scheduled for December 12. However, the primary satellite, TacSat-2, requested additional time to verify some flight software issues. This first launch attempt was scrubbed on December 11 prior to call to stations.

Launch occurred at 0700 local time December 16, 2006. All launch parameters were nominal and there were no range issues. TacSat-2 was deployed approximately 10 minutes after launch, and the LV upper stage performed a contact-collision avoidance maneuver (CCAM) to provide separation between all of the flight elements. The P-POD was then commanded by the upper stage to release the door, which deployed GeneSat-1, and as GeneSat-1 left the P-POD, the satellite's foot switch was activated, energizing the spacecraft. Since this sequence occurred downrange out of telemetry contact, there was no deployment confirmation.

Near the end of the first orbit, approximately 90 min after launch, audible contact with the GeneSat-1 beacon was established with the SRI communication system during the first contact window. No additional contact windows with the SRI station were available until the following day; however, contacts were made by external beacon stations within the university and amateur communities throughout the day. Most of these contacts were audible only, however a few data packets were decoded by one operator during the second orbit; this data showed that spacecraft health was nominal to the extent of analysis supported by beacon data (which included spacecraft temperatures, power state, etc.). Approximately 24 hours after launch, a series of contact windows opened between the vehicle and the SRI station. During the first of these, full communications were established. This included successful reception and data decoding of the beacon channel as well as successful command and telemetry communications through the 2.4 GHz command channel. Over several contacts, satellite health was verified as nominal and positive enough that a mission team decision was made to start the experiment on the following day; we note that the pre-launch expectation was that the experiment would probably not be initiated until approximately the third week of the mission due to anticipated challenges with obtaining precise orbital parameters, establishing functional communications, fully assessing vehicle state of health, etc.

During the next day's series of contact windows (less than 48 hours post-launch), the experiment initiation procedure was successfully executed, starting the 96-hour primary biological experiment. Over the course of those 96 hours, the health of the satellite was monitored and baseline experimental results were downloaded from the satellite. Less than 1 hour after the end of the 96 hour experiment, all baseline experimental data had been downloaded, and less than 30 min after that, all of this data had been archived, processed and converted to data products, and distributed to the mission team.

By Jan 17, approximately 1 month after launch, all operations for executing the primary mission criteria were successfully performed, with results and data products disseminated. Highlights and noteworthy issues during this first month of operation included:

a) A significant period (several days) of high winds (> 65 mph) that damaged the SRI 18-meter dish surface; command operations continued during this period, albiet at a lower throughout; the student ops team worked with SRI personnel to fully repair the mesh;

b) Minor impacts to realtime operations occurred due to a power outage on the Stanford campus that affected internet connectivity in the ground segment as well as a scheduled but unknown firewall reboot at Ames causing intermittent internet connectivity; both issues

resulted in the execution of off-nominal pre-pass procedures such that the mission database (normally operating on a workstation in the Ames MMOC) was operated locally at the SRI station, allowing all contact objectives to be successfully executed by the ops team;

c) Numerous additional issues arose that caused workarounds but did not directly affect realtime operations. These include ~ 4 hours of power outage on the SCU campus (requiring data products to be distributed by e-mail during that time rather than by the data product server), a 10+ power outage in the Ames MMOC, several power outages at the SRI station and/or on the Stanford campus (through which SRI internet service is routed), several scheduled network maintenance activities at Ames, known glitches in the SRI antenna servo power system, etc.

d) Significant attention was focused on how to deal with possible conflicts in use of the SRI station with the MEPSE mission, a battery-operated test satellite developed by The Aerospace Corporation; no conflicts arose during the 4-day MEPSE activity due to the substantially different orbits of the two spacecraft;

e) The student operations team demonstrated extraordinary commitment in working around the clock during a significant academic vacation in order to accomplish the mission.

During the second month of operations, higher resolution payload data was downloaded (exceeding requirements, given the availability of this data). Vehicle state of health studies also continued, and several special data collection procedures were executed (such as the collection and download of high resolution solar panel current data). Furthermore, a number of public demonstrations and operational showcases using the Ames MMOC were also supported during this period.

7.0 Post-Experiment Mission Operations

Post-Experiment operations consisted of further characterizations of the GeneSat-1 spacecraft by the Operations Team. Specifically, a test was designed and executed to measure temperatures and currents from the solar panel arrays. Data from this test was used to verify that the spacecraft was not spinning and by analysis, the acceleration environment was below 10^{-3} g.

Other tests included link margin measurements of the 2.4 GHz radio system, and a power bus characterization of the spacecraft under differing configurations.

On February 21, the Experiment Phase of the mission was officially concluded with a transfer of mission responsibilities from NASA Ames to Santa Clara University. Since that time, and for the remainder of the mission, Santa Clara will continue to collect and report platform characterization operations, use the vehicle to support undergraduate and graduate education through several academic institutions, and to use the vehicle to support a vibrant EPO program in the amateur, university, K-12, and general public communities.

8.0 Test Results

Overall, system performance and test results were outstanding. Temperature, pressure, and humidity were all maintained stably at nominal values and were monitored regularly by sensors. Radiation dose rate, as well as acceleration in three orthogonal axes, were also monitored to track space radiation events and to confirm that the organisms were maintained in a microgravity environment (< 1 milli-g).

The optics subsystem, in both optical density (light scattering) and fluorescence modes, provided stable, low-noise measurements. The fluidic subsystem kept the *E. coli* contained in a state of stasis through a period of more than six weeks prior to deployment and experiment initiation. The *E. coli* were kept inside the wells by the integrated filter membranes on the inlet and outlet of each well. Just before experiment initiation, the temperature of the fluidic card and integrated bio wells was increased by control of the heater to the growth temperature of 34 °C. When temperature was stable within +/-0.5 °C of the setpoint, the valve was opened to provide nutrient to initiate growth.

The *E. coli* began to exhibit growth sufficient to change the light-scattering signal about 2.8 hr after the valve opening. By about 10 hr after growth medium introduction, all 9 biology-containing wells (one fluid well contained no *E. coli* as a control) showed measurable growth. The two 2 different *E. coli* strains had different initiation times and different initial growth rates, as expected. Growth rates were found to be comparable to those recorded for ground-control experiments.

See Figure 8.0-1 for a summary of the *E. coli* growth data.

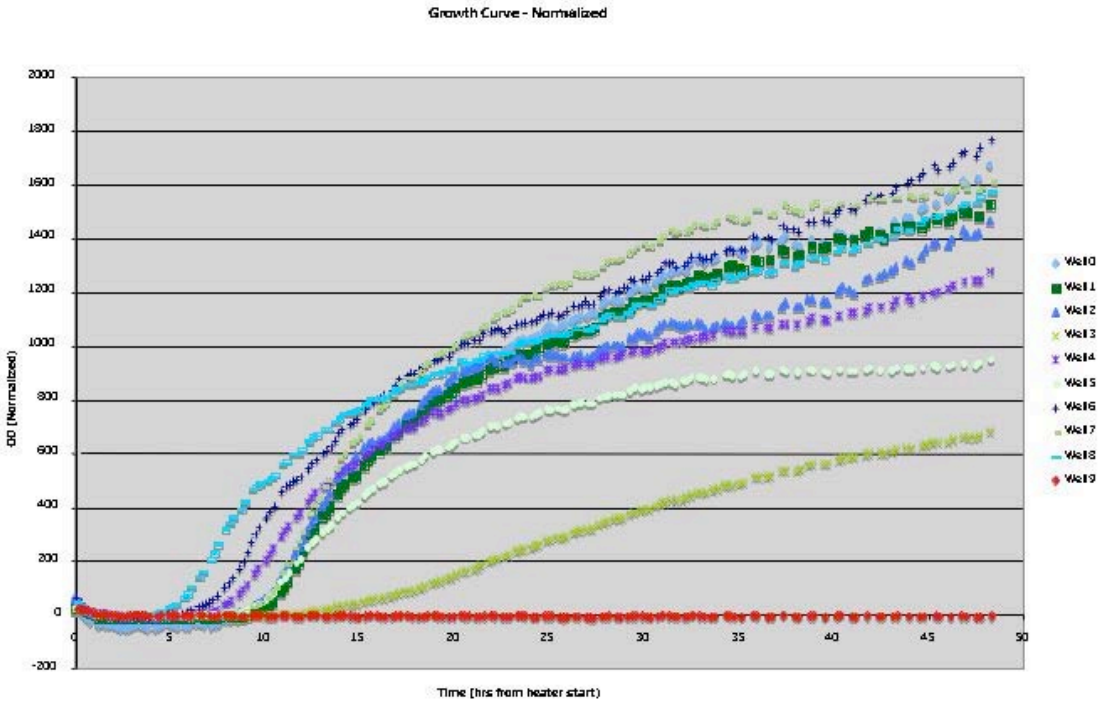

Figure 8.0-1 *E. coli* Normalized Growth Curve

By 9 hours after feeding, the fastest growing well showed the 1st expression of green fluorescent protein. By about 20 hr after growth start, 6 of 9 biowells showed definite green fluorescence; eventually, the remaining 3 biowells showed signals from GFP as well.

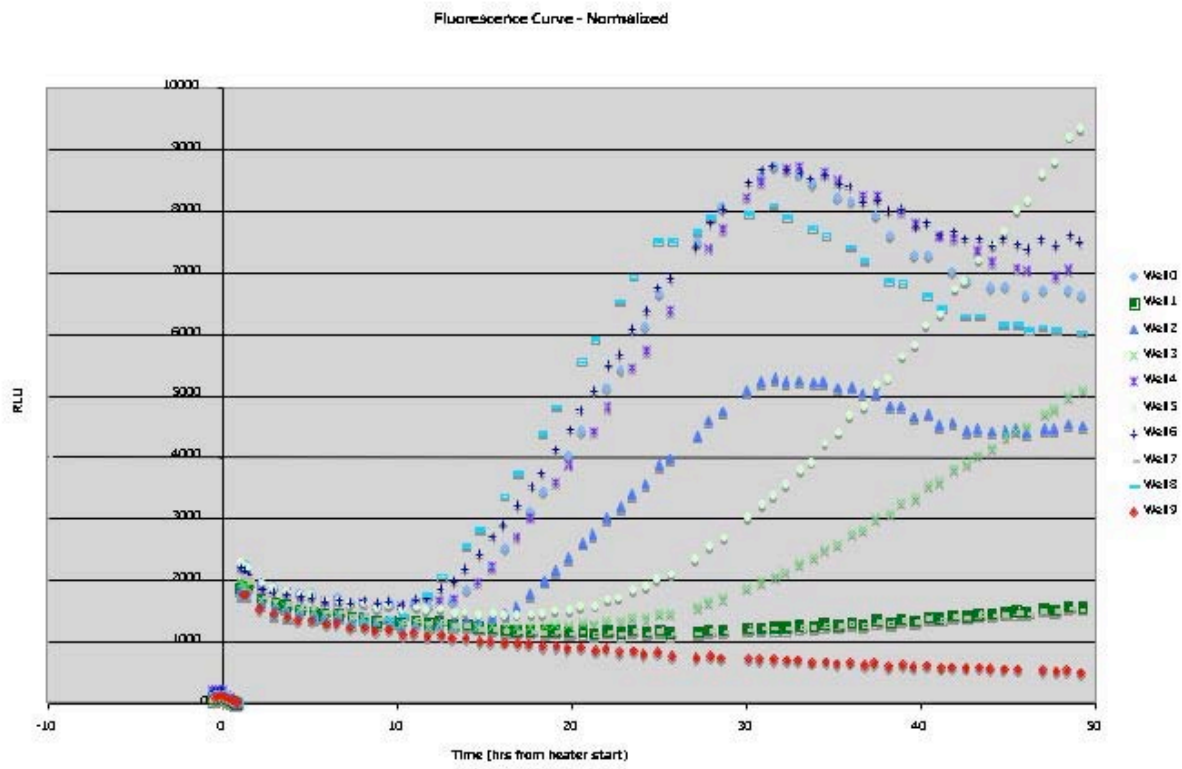

Figure 8.0-2 Normalized Fluorescence Curve

Temperature inside the payload pressure vessel remained remarkably stable, sitting in a band < 1°C wide as the satellite traveled in and out of sunlight. The pressure and relative humidity clearly showed the effects of the orbital period (and consequent change of the temperature of the outer vessel wall), as expected; the temperature of the fluidic card barely showed any sign of the large external temperature swing, due to good thermal isolation; and the optical readings showed no sign at all of the major temperature and illumination swings going on outside the vessel. The orbital period had no measurable direct effect on the biology.

9.0 Lessons Learned

The major technical lessons learned from the GeneSat-1 mission were mapped back to risks, which were either identified early in the project life cycle, or were discovered as the project progressed.

Risk Title: Late delivery of biology payload impacts test time.
Lesson: Using a GeneSat-1 lesson learned a multi-path bioviability test regime should be specified. In GeneSat, overdependence on one type of *E. coli* led to critical path schedule problems when it was determined that the biology was underperforming. Test plans should

ensure viable biology is selected from multiple candidates prior to the time it is need for integrated system tests.

Risk Title: Software test support not sufficient.
Lesson: Software test phases should be clearly defined. Specific functional tests must cover all requirements traceable to software and demonstrate there are no errors under simulated mission conditions including durations of operation as much as is practicable.

Risk Title: MCU Interrupts interfere with TimeStamp Function
Lesson: In GeneSat-1 operations it was discovered that some software interrupts of the MCU interfered with the time stamp functions.

In future missions, the integrated behavior of the MCU with hardware and software interrupts should be evaluated (inspected) and tested to verify that this error cannot occur after software has been modified to remove "time slips" caused by this problem.

Risk Title: Biocompatibility and Sterility of Materials In contact w/ Biology
Lesson: In the GeneSat bio-fluidics development test plan all items that could contact the biology were evaluated for effect on biology growth behavior. This test series was successful in determining acceptable materials and in baselining biology growth behavior. This approach should be repeated for future missions to avoid any late discovery of variable growth behavior that could lead to added uncertainty and extended growth testing on the schedule critical path.

Risk Title: Valve Fails Open Due to Media Crystallization
Lesson: On GeneSat-1 it was discovered that the magnesium sulfate crystal precipitate is caused by an incorrect 0.1 molar solution preparation (vs. the specified 0.01 molar solution).

Response 1: The media preparation procedures (as with all procedures) are required to be monitored by a second, experienced set of eyes. (It is not sufficient to merely review the data sheet after preparation because an inexperienced Technician can do one thing and write down something else -- like slipping a decimal point.)

Response 2: Avoid use of gas-type valves for fluid applications.

Response 3: Include a procedure step to verify valves do not leak after fluids are loaded.

Project Lessons Learned

From a project perspective, positive lessons learned included establishing small co-located working teams for the development and test of the GeneSat-1 hardware and software systems. Team members were able to follow the entire project through it's life cycle, versus handing over subsystems and tasks at various phases of the project. This meant that the same engineer/scientist that defined, developed, tested and prepared the various systems were part of the mission management team.

Also, the involvement of local universities at various points within the project cycle was positive. Students, along with their professor(s), were integrated into the project team as equal members. This provided the project with key skills and functions for specific parts of the mission (P-POD – Cal Poly SLO and Ground Segment – Santa Clara Univ.).